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Telecommunication Aspects of a Manned Mars Mission

W. K. Victor
R. Titsworth
E. Rechtin

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CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA

August 20, 1963

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A landing party on the surface of Mars will be able to maintain almost continuous high-quality communications with the Earth by using a synchronous, communications-relay satellite network established in orbit around Mars before the manned expedition leaves the Earth. It is shown that real-time television is possible in either direction – that is, from Earth to Mars and from Mars to Earth – even at the maximum Earth–Mars distance of 400 million kilometers and by utilizing conventional devices. The principal problem appears to be one of engineering these devices so that they possess adequate long life and reliability to accomplish the mission. An emergency teletype link is capable of direct Earth–Mars communications (by-passing the orbital relay) when the landing party's side of Mars is facing the Earth. Temporary loss of communications will occur at semisynodic periods of approximately 13 months when the planets are in opposition or in conjunction. A communications black-out occurs when the Sun enters the main beam of either the Earth-based or the Mars-orbiter antenna, and computational results are included which indicate that this should not be a serious problem if it is planned for during the design of the mission.

Author

I. INTRODUCTION

This report describes a communication system that utilizes conventional devices and is capable of maintaining almost continuous, high-quality communication with our proposed Mars-bound explorers from the time of Earth lift-off to Mars touch-down and return. However, in arriving at any systems design, it is necessary to make certain assumptions and to assign certain priorities to competing characteristics. These self-imposed characteristics and their related assumptions form the prelude to the description of this communication system.

The most significant assumption is that the communication link should not be constrained by the mission profile, i.e., the length of the journey, the type of Earth–Mars trajectory, the type of propulsion systems, the landing procedure, the landing area, etc. Also, it should not be affected appreciably by the necessity to maintain continuous radio contact with the Earth station. In connection with this assumption, it was determined that the maximum Earth–Mars range between the present year and 1980 was approximately 400 million kilometers. Consequently, it was assumed that the system would have to function satisfactorily at that range in order to satisfy these particular conditions.

The second assumption is that continuous 24-hr contact is desired for the entire journey. However, 10 to 20 days per year of outage was considered permissible provided that these days occurred at predictable times and, particularly, did not occur during periods of critical operations.

The third assumption is that high-quality communication is a requirement for manned, interplanetary space flight. High-quality communication is defined as a communication system having modulated bandwidths up to 1 megacycle and an output signal-to-noise ratio of at least 40 db. For the noncommunications specialist, this can be translated to mean that there is the capability for high-quality television of a commercial variety similar to that displayed in homes. Moreover, this high-quality television could be transmitted in either direction, i.e., from Earth to spacecraft or from spacecraft to Earth. Transmission to the spacecraft could, if for no other reason, be of value in entertaining the crew during their long voyage. Transmission from the spacecraft to Earth would be for the purpose of gathering video data of the surface of Mars. This would require that communication be operative even at the maximum Earth–Mars range, 400 million kilometers.

An interesting fact is disclosed by a comparison of performance between commercial television and that of the space-communications system. The maximum range of commercial television is approximately 125 miles, or about 200 kilometers. The space-communications system must be able to transmit a comparable picture two million times as far.

The fourth assumption is that conventional devices would be utilized, and, furthermore, every component and technique suggested should exist at the present time and should require only engineering refinements to ensure a several-year life span without maintenance or adjustment in the interplanetary-trip environment. This is not to say that when the time comes to launch this vehicle, nonconventional devices will not be used. However, from a communications standpoint, it is feasible to consider even at this time a manned-Mars exploration. Furthermore, communication-satellite technology may be expected to solve many of the remaining problems of long life and reliability during the next decade.

The last assumption is that it is believed that some redundancy is desired in order to increase the reliability. The proposed communication system does provide for partial communication, i.e., a reduced communications capability after partial failure rather than no communications following partial failure.

II. SYSTEM CONFIGURATION

Figure 1 presents the complete picture of the communication scheme. The principal feature of the system is that there will be three communications-relay satellites which are synchronized around Mars. The basic communication channel is labeled channel I. This channel is in the S-band, and it transmits on a frequency of 2115 Mc and returns on approximately 2300 Mc. This band of frequencies has been allocated, at least within the United States, for these basic communications. Channel I′ and channel I″ are also frequencies in the same region, though slightly offset.

A second major channel (channel II) is at UHF and is indicated in Fig. 1 as 380 Mc, going to a landing craft and 400 Mc for the returning signals. The following assumptions as to the manner in which a landing craft might be brought to Mars have been borrowed from the proposed *Apollo* project. It is assumed that the landing craft would be a separable part of the Mars spaceship. Also, it is assumed that the landing craft will communicate with the spaceship or communicate directly with the relay stations. In addition, the channel labeled channel III (Fig. 1) is an emergency channel that will permit the landing craft to communicate directly with the Earth. The landing craft will be equipped with a 10-ft diameter antenna (not illustrated). It should be noted that the orbiting relays and the spaceship are illustrated as having two antennas. One, a 4-meter diameter dish, is in-

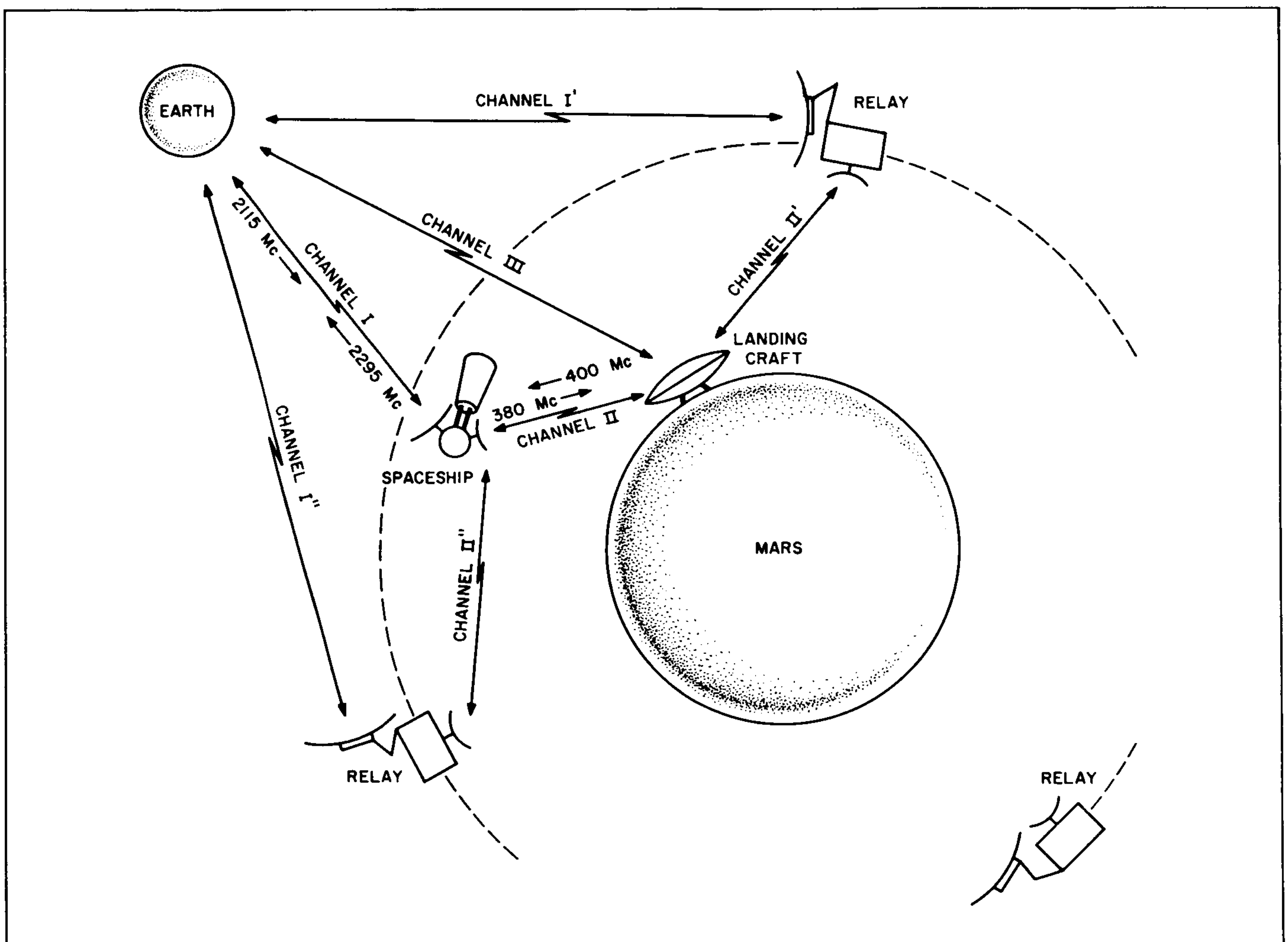

Fig. 1. Synchronous Mars communication satellites

tended for channel-I communications, and the other is a 10-ft diameter antenna intended for channel-II communications.

Figure 2 shows the geographic locations of stations on Earth that are presently used in the unmanned planetary network of stations controlled from the United States. These are indicated at longitudes approximately 120 deg apart and distributed latitudinally within a 60-deg-wide band around the equator. It is surmised that a similar network of Earth-based stations might be used during the manned-Mars mission.

One of the principal, conventional communications devices to be employed in the proposed system is a very large surface antenna depicted in Fig. 3. The diameter of the parabola is 210 ft; the illustration is a model of such a device. To illustrate the comparative size of the antenna, a truck-trailer combination model in the same scale as that of the antenna model appears at the left of the antenna base. The antenna has become a conventional device, since two of these have already been built, one in England and one in Australia. The antenna proposed for this space-communication system is to be patterned somewhat after the Australian antenna which is 210 ft in diameter. The principal difference would be that the proposed antenna would be designed to withstand greater wind loads and would be capable of being pointed at the horizon (zero degrees elevation), whereas the Australian unit is limited to a minimum elevation angle of 30 deg.

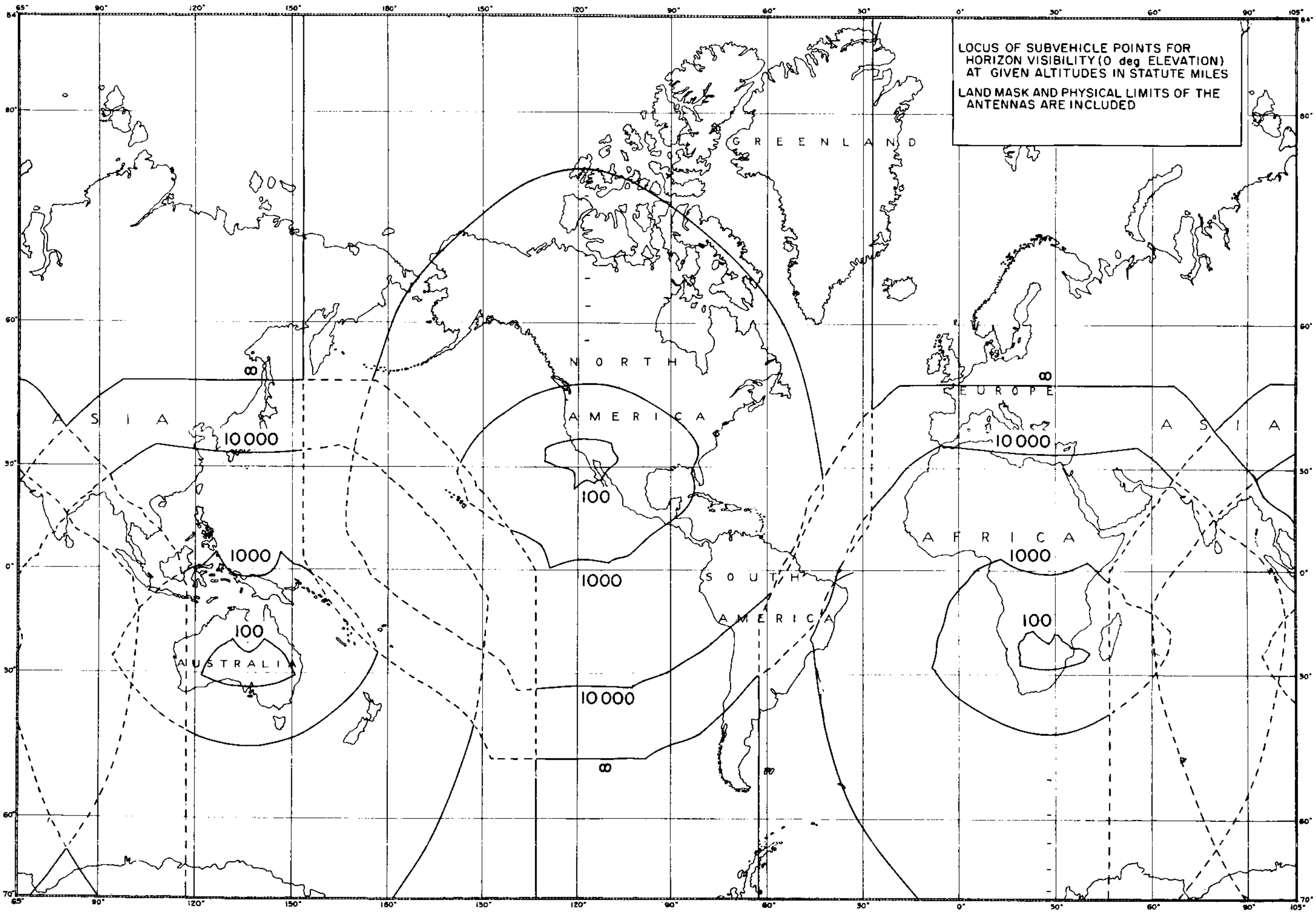

Fig. 2. DSIF coverage map

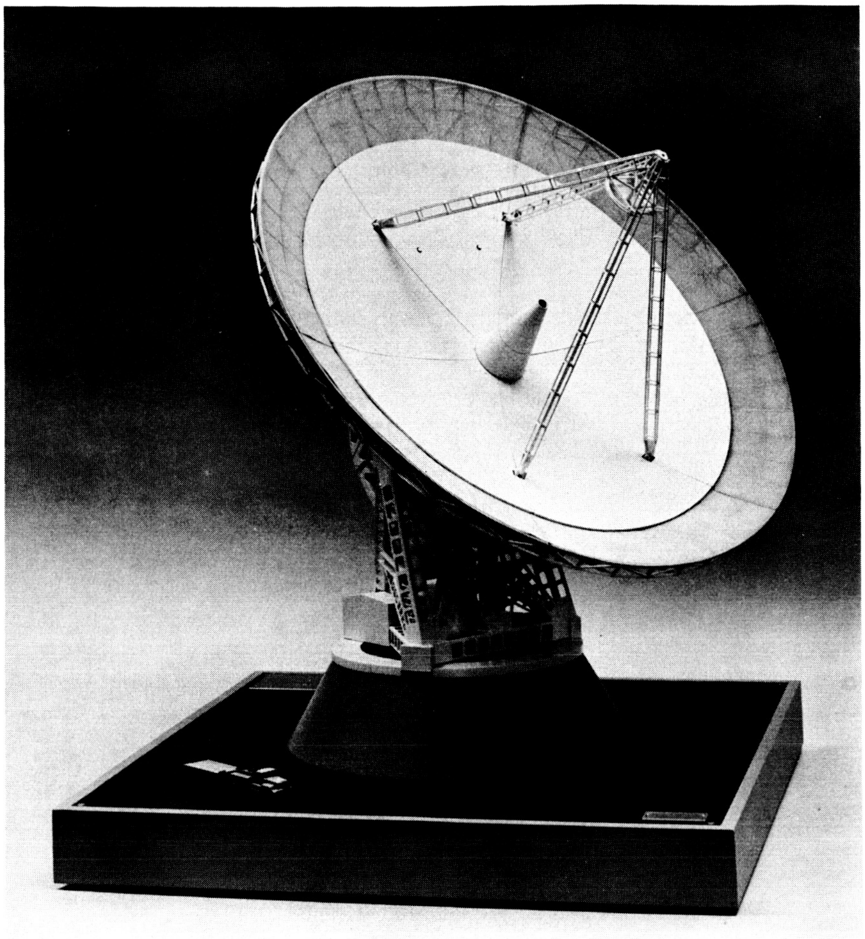

Fig. 3. Model of 210-ft parabolic antenna

III. COMMUNICATION LINKS

A. Earth-to-Orbiting Relay or Spaceship

The information contained in Table 1 corresponds to channel I, the 2115-Mc Earth-to-orbiting relay, or spaceship link. The principal parameters are a ground transmitter power of approximately 400 kw, with fairly negligible losses, an Earth-based antenna of 210 ft in diameter which provides about 60.7-db gain, and 4-meter-diameter (13-ft) antennas on both the spaceship and the orbiting relays. A 4-meter antenna is not too large by present-day standards, and it would produce a gain of about 37 db. The beamwidth of the Earth-based antenna at the given frequency (2115 Mc) and with the given gain (60.7 db) would be 1/10 of a degree at the half-power points, whereas the half-power beamwidth of the spacecraft's and the orbiting relays' 4-meter antennas would be about 2 deg. This combination would produce an expected signal level of -88 dbm at a distance of 400 million kilometers. When used with a receiver (probably a parametric amplifier) having an operating temperature of 150°K and a bandwidth of 1 Mc, the resultant threshold would be -116.8 dbm. When these two dbm values are differenced, the expected rms signal-to-noise ratio is $+28.8$ db, which would be sufficient in itself for high-quality television. These numbers, of course, are gross estimates. It should be pointed out, however, that this value of $+28.8$ db should be considered within plus and minus 10 db of being correct. The plus 10 db is reasonable since there are some developments that might be expected in the area of data compression, coding theory, modulation theory, etc., which could provide improvement. Some of the problems involved are not indicated (e.g., antenna pointing losses, modulation losses, etc.), and these contribute negatively.

Table 1. Communication system parameters for Earth-to-orbiting-relay link at 2115 Mc

Ground transmitter power (400 kw, average), dbm	+ 86.0
Transmission line and diplexer loss, db	− 0.3
Ground transmitter antenna gain (210 ft diameter, 46% efficiency), db	+ 60.7
Polarization loss (circular to circular), db	− 0.1
Space loss $\left(\frac{\lambda}{4\pi R}\right)^2$ for 2.115 kMc and 400×10^6 km, db	−271.5
Orbiter antenna gain (13.1 ft diameter, 60% efficiency), db	+ 37.5
Transmission line and diplexer loss, db	− 0.3
Expected signal level, dbm	− 88.0
Receiver threshold (T = 150° K, bw = 1 Mc), dbm	−116.8
Expected rms signal-to-rms noise ratio (bw = 1 Mc), db	+ 28.8
Digital improvement factor (7-bit quantization, $P_e < 10^{-6}$), db	+ 13.2
Expected video P-P-signal-to-rms-noise ratio (bw = ±7 Mc), db	+ 53.0

The possible digital improvement factor (+13.2 db) indicated in Table 1 is analogous to a common phrase, "FM improvement factor", which is employed in communication technology. It signifies a trade-off between a bandwidth and a signal-to-noise ratio. So by utilizing this technique and increasing the bandwidth from 1 to ±7 Mc, for example, the expected peak-to-peak signal-to-rms-noise ratio would be 53 db, which is quite acceptable by present-day standards.

B. From Orbiting Relay and Spaceship to Earth

Considering the link from the orbiting relay or spaceship to the Earth, as shown in Table 2, the principal parameter assumed is a transmitter power of 10 kw. Although 10-kw amplifiers are quite common today, they are not common on board spacecraft. The principal problems, of course, are supplying the primary power and developing a suitable cooling system. It must be realized that the primary power required would have to be on the order of 30 to 40 kw to compensate for system efficiency losses, and a cooling system of comparable size would be needed. Transmitting 10-kw of power at 2295 Mc over the 4-meter-diameter antenna through 400 million kilometers of space to the 210-ft-diameter Earth-based antenna, the received signal level would be -103.7 dbm. One important parameter is that the receiving system's temperature is assumed to be 25°K. Successful operation can be achieved on a continuous basis at the present time with the Earth-based system's temperature between 35 to 40°K. Therefore, 25°K is considered to be quite a conservative estimate of future capability and would give an expected rms signal-to-noise ratio of $+20.9$ db. With a corresponding improvement factor and bandwidth

Table 2. Communication system parameters for orbiting-relay-to-Earth link at 2295 Mc

Transmitter power (10 kw, average), dbm	+ 70.0
Transmission line and diplexer loss, db	− 0.3
Antenna gain (13.1 ft diameter), db	+ 37.8
Polarization loss (circular to circular), db	− 0.1
Space loss $\left(\frac{\lambda}{4\pi R}\right)^2$ for 2.295 kMc and 400×10^6 km	−271.8
Ground antenna gain (210 ft diameter, 50% efficiency), db	+ 61.0
Ground transmission line and diplexer loss, db	− 0.3
Expected signal level, dbm	−103.7
Receiver threshold ($T = 25°$ K, bw = 1 Mc), dbm	−124.6
Expected rms signal-to-rms noise ratio (bw = 1 Mc), db	+ 20.9
Digital improvement factor (7-bit quantization, $P_e = 10^{-5}$), db	+ 18.7
Expected video *P-P*-signal-to-rms-noise ratio (bw = ±7 Mc), db	+ 50.4

Table 3. Communication system parameters for orbiting-relay-to-Mars-capsule link at 380 Mc

Transmitter power (1 kw, average), dbm	+ 60.0
Transmission line and diplexer loss, db	− 0.3
Orbiter antenna gain (10 ft diameter, 52% efficiency), db	+ 18.8
Polarization loss (circular to linear), db	− 3.0
Space loss $\left(\frac{\lambda}{4\pi R}\right)^2$ for 380 Mc and 20×10^3 km, db	−170.2
Capsule antenna gain, db	+ 6.0
Capsule transmission line and diplexer loss, db	− 0.3
Expected signal level, dbm	− 89.0
Receiver threshold ($T = 300°$ K, bw = 1 Mc), dbm	−113.8
Expected rms signal-to-rms noise ratio (bw = 1 Mc), db	+ 24.8
Digital improvement factor (7-bit quantization, $P_e < 10^{-6}$), db	+ 17.4
Expected video *P-P*-signal-to-rms-noise ratio (bw = ±7 Mc), db	+ 53.0

trade-off, a +50.4-db-peak-to-peak signal-to-rms-noise ratio could be achieved.

C. From Orbiting Relay or Spaceship to Landing Craft

Table 3 contains a list of the pertinent parameters related to this link. The orbiting relay or spaceship will be transmitting 1 kw of power at 380 Mc through the 10-ft diameter antenna having a gain of +18.8 db. This is a gain-limited situation because the orbiting relay or spaceship points its antenna directly at the center of Mars, and the beamwidth covers the entire projected surface of the planet. The +18.8-db gain assumes that the orbiting altitude of the relay or the spaceship is about 17,000 km, and the range to the landing craft is 20,000 km. The antenna gain on the landing craft is +6 db, which means that it is sufficiently broad that the landing party is not required to aim the antenna at the orbiting relays. The expected signal level is then −89.0 dbm. The receiver threshold, assuming a parametric amplifier and a system temperature of 300°K, is −113.8 dbm. (This higher temperature is caused by the increased level of cosmic noise at frequencies in the range of 380 to 400 Mc.) The received rms signal-to-noise ratio in the same 1-Mc bandwidth is then +24.8 db. By use of the bandwidth spreading technique, an improvement of +17.4 db and a resulting peak-to-peak signal-to-rms-noise ratio of +53 db is achieved.

D. From Landing Craft to Orbiting Relay or Spacecraft

Table 4 lists the pertinent figures related to the communications link from the landing craft to the orbiting relay or spaceship. Here the landing craft transmits 1-kw of power at 400 Mc through its antenna with a +6.4-db gain over a range of 20,000 km to the orbiter's 10-ft-diameter antenna having a gain of +19.2 db. The received rms signal-to-noise ratio is +25.2 db. This increases to +53 db peak-to-peak signal-to-rms-noise ratio with the indicated bandwidth expansion. Thus, this orbiter-to-surface link is compatible with the other elements of the communication system.

E. Between the Earth and Landing Craft (Emergency Mode)

Channel III (Fig. 1) is the emergency-mode channel which permits direct communications between the Earth and the landing craft. The Earth-based transmitter radiates 400 kw of power at 380 Mc from its 210-ft-diameter

Table 4. Communication system parameters for Mars-capsule-to-orbiting-relay link at 400 Mc

Capsule transmitter power (1 kw, average), dbm	+ 60.0
Transmission line and diplexer loss, db	− 0.3
Capsule antenna gain, db	+ 6.4
Polarization loss (linear to circular), db	− 3.0
Space loss $\left(\frac{\lambda}{4\pi R}\right)^2$ for 400 Mc and 20 × 10^3 km, db	−170.6
Orbiter antenna gain (10 ft diameter, 51% efficiency), db	+ 19.2
Orbiter transmission line and diplexer loss, db	− 0.3
Expected signal level, dbm	− 88.6
Receiver threshold (T = 300° K, bw = 1 Mc), dbm	−113.8
Expected rms signal-to-rms noise ratio (bw = 1 Mc), db	+ 25.2
Digital improvement factor (7-bit quantization, $P_e < 10^{-6}$), db	+ 17.0
Expected video P-P-signal-to-rms-noise ratio (bw = ±7 Mc), db	+ 53.0

antenna toward the landing craft antenna which has +6-db gain. These conditions produce an expected rms signal-to-noise ratio of +16.2 db in a bandwidth of 3 kc. This is a reduced communication capability, but it does mean, however, that one-way voice communication from persons on Earth to the landing party is possible. This capability could be increased to +22.2 db without coding, or to +28.8 db with coding and would be quite satisfactory for voice communication one-way. Table 5 shows the communication system parameters for this emergency mode of operation.

Signals in this emergency mode come from the landing craft back to Earth at 400 Mc. At the maximum range (400 million kilometers), 1-kw of power radiated from Mars through a +6.4-db antenna, will produce an expected rms signal-to-noise ratio at the Earth-based station (assuming a 75°K-system temperature), of +11.8 db in a 100-cps bandwidth. This means that emergency mode communications from the landing craft to Earth would have to be messages teletyped at a bit rate of 180 to 275 bits per second, as indicated in Table 6. Increased data rates could be achieved by providing the landing party with a medium-sized, lightweight directional antenna which could be aimed optically at the Earth.

Table 5. Communication system parameters for Earth-to-Mars landing capsule at 380 Mc (emergency mode)

Transmitter power (400 kw, average), dbm	+ 86.0
Transmission line and diplexer loss, db	− 0.3
Ground antenna gain (210 ft diameter, 48% efficiency), db	+ 45.4
Polarization loss (circular to linear), db	− 3.0
Space loss $\left(\frac{\lambda}{4\pi R}\right)^2$ for 380 Mc and 400 × 10^6 km	−256.2
Capsule antenna gain, db	+ 6.0
Transmission line and diplexer loss, db	− 0.3
Expected signal level, dbm	−122.4
Receiver threshold (T = 300° K, bw = 3 kc), dbm	−138.6
Expected rms signal-to-rms noise ratio (bw = 3 kc), db	+ 16.2
Digital improvement factor (4-bit quantization, $P_e = 5 \times 10^{-4}$), db	+ 6.0
Expected rms signal-to-rms noise ratio (bw = ±12 kc), db	+ 22.2
Digital improvement factor (16,5) code (5-bit quantization, $P_e = 8 \times 10^{-5}$), db	+ 12.6
Expected rms signal-to-rms noise ratio (bw = ±48 kc), db	+ 28.8

Table 6. Communication system parameters for Mars-landing-capsule-to-Earth at 400 Mc (emergency mode)

Capsule transmitter power (1 kw, average), dbm	+ 60.0
Transmission line and diplexer loss, db	− 0.3
Capsule antenna gain, db	+ 6.4
Polarization loss (linear to circular), db	− 3.0
Space loss $\left(\frac{\lambda}{4\pi R}\right)^2$ for 400 Mc and 400 × 10^3 km, db	−256.6
Ground antenna gain (210 ft diameter), db	+ 45.8
Transmission line and diplexer loss, db	− 0.3
Expected signal level, dbm	−148.0
Receiver threshold (T = 75° K, bw = 100 cps), dbm	−159.8
Expected rms signal-to-rms noise ratio (bw = 100 cps), db	+ 11.8
Information rate at $P_e = 3 \times 10^{-3}$, bits/sec	180
Information rate at $P_e = 3 \times 10^{-3}$, (16,5) code, bits/sec	275

IV. COMMUNICATION CAPABILITY

As mentioned earlier, communication is expected to be virtually continuous and limited only by direct rays from the Sun entering either the Earth-based antenna or those at the planet. Figure 4 shows the Sun–Earth–Mars geometry to ascertain interference by the Sun. At conjunction (the time when the Sun–Earth–Mars angle is 0 deg), the Sun is in the Earth-based antenna, and it is also in the antennas at the planet. At opposition, where the Sun–Earth–Mars angle is 180 deg, the Sun is in the Mars antennas only. This would black-out the communication capability for about 10 to 20 days with the antenna placements and with the systems temperatures that have been assumed here.

The relative communications capability from Earth to Mars is shown in Fig. 5 for the five-year period commencing 1975. Zero db corresponds to a range of about 400 million kilometers. As can be seen in the graph, there is approximately 12- to 14-db difference between the maximum and the minimum capability. The Sun enters the Mars antennas twice during this five-year period when the Earth and Mars are in conjunction. Additionally, there are three semisynodic periods of interference that occur at opposition; interference thus occurs at a frequency of approximately once every 13 months.

The communications capability from Mars to Earth is depicted in Fig. 6 for the same five-year period. The Sun enters the Earth-based antenna twice in the five years during the periods of conjunction.

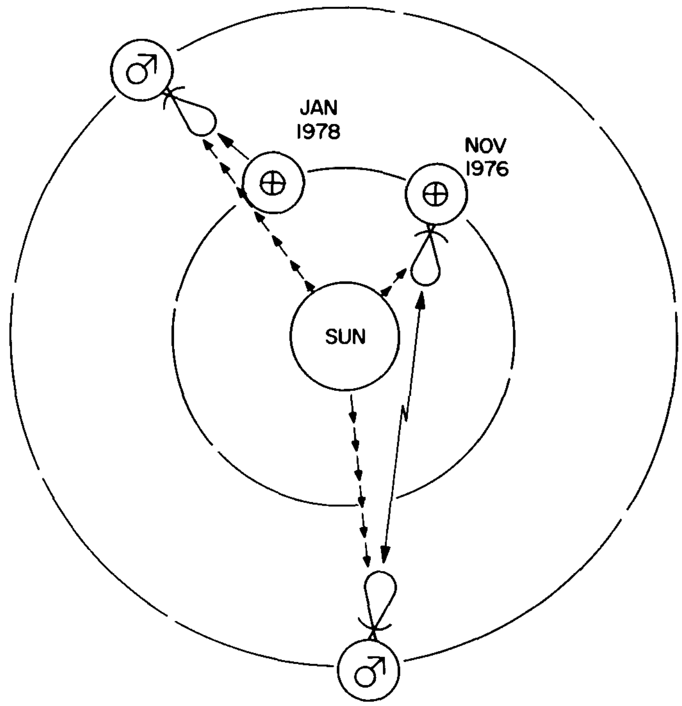

Fig. 4. Sun-Earth-Mars geometry to ascertain rf interference by the Sun

Figure 7 indicates the digital-improvement factor possible by the use of digital-data transmission, both with and without coding.

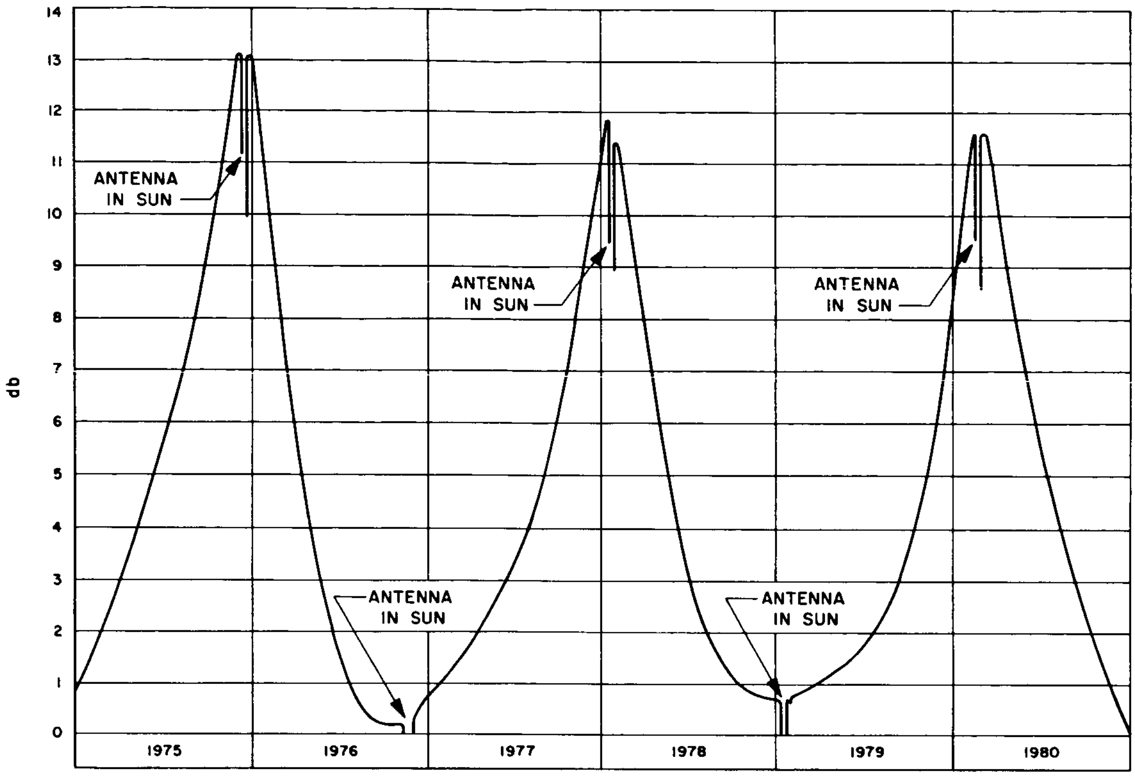

Fig. 5. Relative communication capability from Earth to Mars

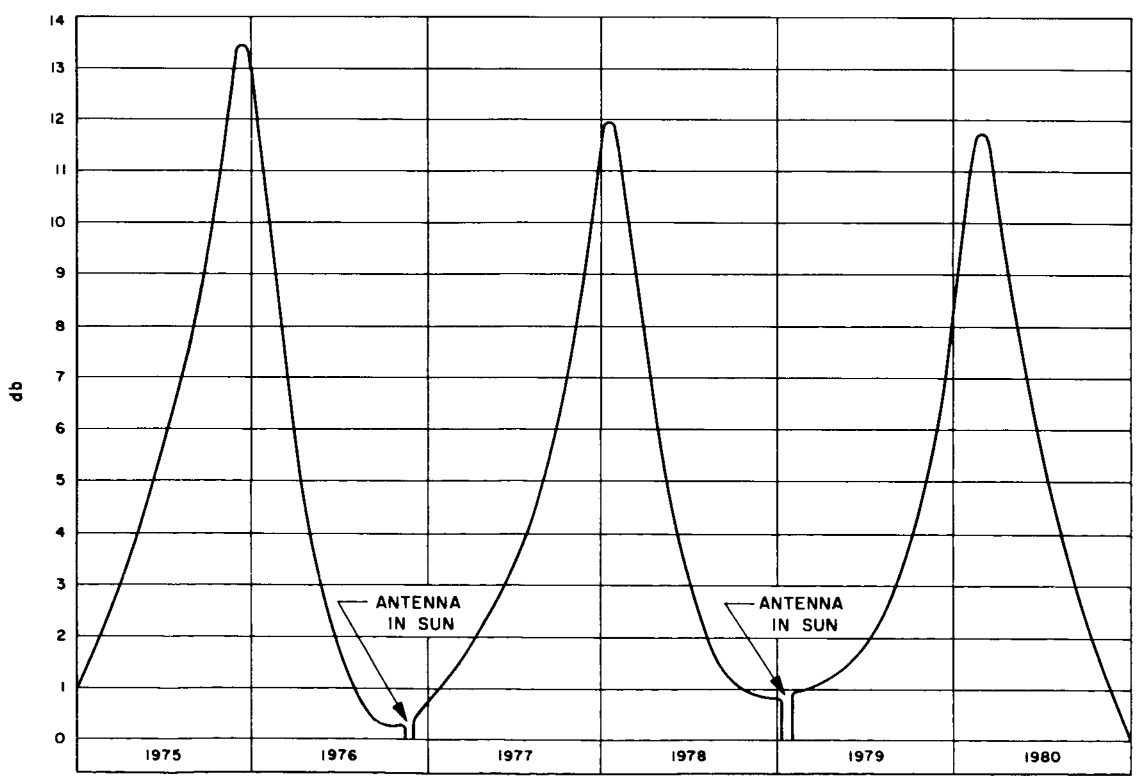

Fig. 6. Relative communication capability from Mars to Earth

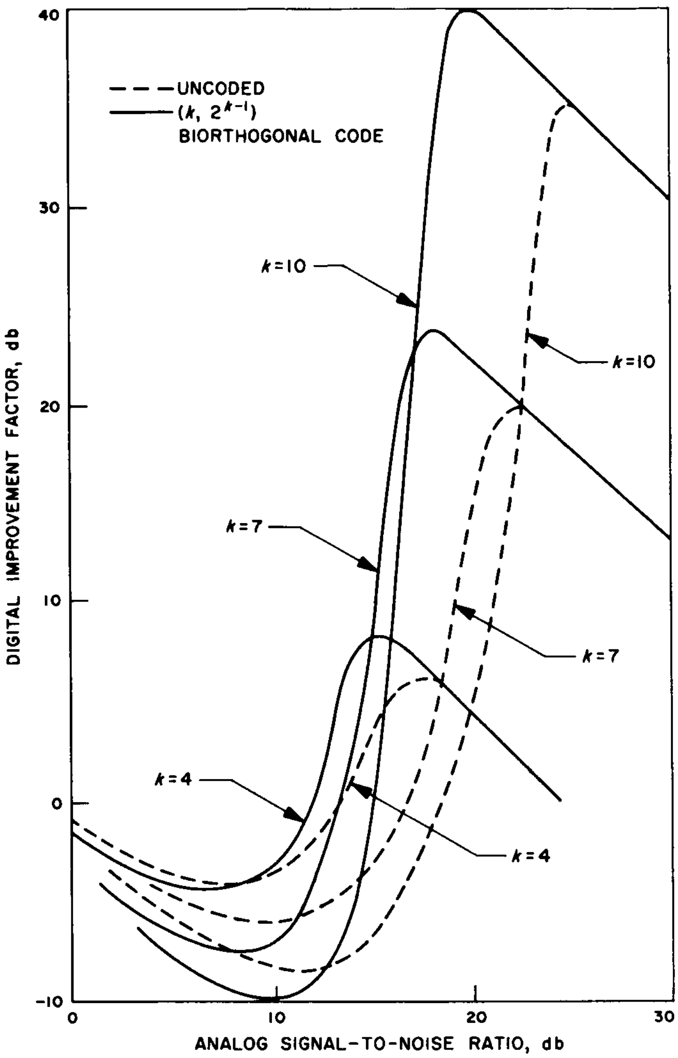

Fig. 7. Advantage of digital data transmission with and without coding, using k-bits quantization

V. SUMMARY

In summation, the system as described should be capable of maintaining almost continuous, high-quality communication with a group of Mars-bound astronauts from the time they depart Earth to the time they return. The system is dependent upon the successful establishment of a synchronous satellite network around Mars before the expedition is launched. The system utilizes state-of-the-art, conventional devices which should be capable of transmitting real-time television pictures in either direction even at the maximum Earth–Mars range of 400 million kilometers. The major problem areas can be overcome by re-engineering these devices in order to achieve the long life and reliability necessary to accomplish the mission. Considerable improvement in the life and reliability of components can be expected within the next decade as a natural result of developments in current Earth-satellite-communication projects. A particularly important feature of the system described is the freedom it offers to groups designing mission profiles in that virtually any type of trajectory or Mars entry plan can be accommodated without affecting the ability of the links to provide continuous communications during critical periods. Two basic channels have been provided, one at S-band for the principal Earth–Mars channel, and one UHF channel at 400 Mc for the orbiting relays and spaceship to Mars landing craft. An emergency Earth–Mars channel at UHF has been added for use in the event the S-band were to fail. Additional redundancy is also provided through the use of three synchronous-communication-relay satellites. Some reduction in communications capability will result if there is a failure of any one of the relay stations; however, even in this case communication could be continued on a partial basis.

The study of the Sun–Earth–Mars geometry shows that temporary loss of communication, possibly in the order of 10 to 20 days, will occur at semisynodic periods of approximately 13 months. Although a communications black-out does occur when the Sun enters the main beam of either the Earth-based or the Mars antennas, this is not considered a serious limitation since it occurs so infrequently and because it can be predicted accurately during the planning phases of the mission.